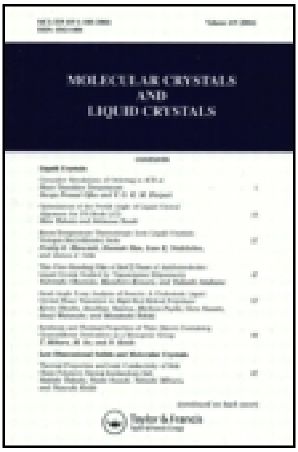

Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl20

An Electro-Optically Tunable Bragg Reflector Based on Liquid Crystals

G. Gilardi [a] , R. Asquini [a] , A. d'Alessandro [a] & G. Assanto [b]

[a] Dipartimento di Ingegneria dell'Informazione, Elettronica e Telecomunicazioni, Sapienza University of Rome Via Eudossiana 18 - 00184 Rome - Italy

[b] NooEL-Nonlinear Optics and OptoElectronics Lab, Università di Roma "Roma Tre", Via della Vasca Navale 84 - 00146, Rome - Italy

Version of record first published: 07 Oct 2011

Mol. Cryst. Liq. Cryst., Vol. 549: pp. 62–68, 2011

ISSN: 1542-1406 print/1563-5287 online
DOI: 10.1080/15421406.2011.581137

An Electro-Optically Tunable Bragg Reflector Based on Liquid Crystals

G. GILARDI,[1,*] R. ASQUINI,[1] A. D'ALESSANDRO,[1]
AND G. ASSANTO[2]

[1]Dipartimento di Ingegneria dell'Informazione, Elettronica e Telecomunicazioni, Sapienza University of Rome Via Eudossiana 18 - 00184 Rome - Italy
[2]NooEL-Nonlinear Optics and OptoElectronics Lab, Università di Roma "Roma Tre", Via della Vasca Navale 84 - 00146, Rome - Italy

In this paper we report the analysis of a distributed feedback guided-wave reflector in liquid crystals and we describe the main properties of the device. The device is based on a comb-shaped interdigitated electrodes and a liquid crystal slab. The device shows a wide tuning range exceeding 100 nm covering C and L bands for wavelength division multiplexing.

Keywords Optical waveguides; liquid crystals; electro-optic effect

Introduction

Bragg reflectors are key elements for a variety of applications such as spectral filtering [1,2], tunable lasers [3], polarization dispersion compensation and manipulation [4], multi/demultiplexing [5], spectrometry [6], and sensing [7]. Among the waveguides employed to date we mention those in polymers [8], silicon-on-insulator (SOI) [9], hollow capillaries [10], lithium niobate [11], silica [12], metal-insulator-metal [13] and liquid crystals [14–18].

Bragg tuning has been proposed and implemented thermo-optically [9], mechanically [19], acousto-optically [20], electro-optically [14] and opto-optically [21]. The largest thermo-optic tunings were obtained in SOI rib guides (18 nm) [9] and in polymeric gratings (between 20 and 30 nm) [3,8]. Wavelength shifts of about 45 nm were reported by tensile strain on a flexible polymeric waveguide [2] and of more than 90 nm in silica via mechanical beam-bending [19]. Tuning over 76 nm was achieved acoustically in $LiNbO_3$ [20], and over 160 nm by piezoelectric actuators in hollow waveguides [10]. Tunable Bragg gratings were also realized with liquid crystals exploiting their large electro-optic response [22].

Device Geometry

The device structure is a planar waveguide as sketched in Figure 1. It consists of a nematic liquid crystal (NLC) layer sandwiched between two parallel glass plates with refractive index 1.5 at $\lambda = 1550$ nm. The inner face of one of them is coated with a pair of comb-shaped interdigitated 100 nm thick ITO transparent electrodes as shown in Figure 1.

*Corresponding author. E-mail: gilardi@die.uniroma1.it

Both electrodes are periodic along z and symmetrically located with respect to $y = 0$. ITO electrodes are 100 nm thick, with complex refractive index $1.3 + i0.1$ at $\lambda = 1550$ nm. The electrode dimensions are a = b = 500 nm, c = 250 nm, t = 250 nm and T = 500 nm. For single-mode operation at $\lambda = 1550$ nm we consider an NLC layer thickness h = 1 μm. For the NLC we consider the standard mixture E7 (with extraordinary refractive index $n_e = 1.689$ and ordinary refractive index $n_o = 1.5$ @1550 nm). Planar anchoring of the NLC molecular director (optic axis) is assumed at the glass interfaces. We also assume a pre-twist angle of about 4° with respect to z in order to eliminate the Fréedericks threshold [19, 23].

Working Principle

The electrode topology and the NLC parameters need to be selected in order to achieve high coupling between an injected transverse electric (TE) optical beam and the voltage induced Bragg grating over a finite propagation distance. Moreover, the applied voltage is intended to increase the index in an NLC finite region along y ensuring two-dimensional (2D) transverse confinement of light injected in a thin film slab. The external voltage forces the rotation of the director in the bulk, yielding the formation of a periodic grating defined by the electrode topology.

Figure 2 shows molecular reorientation without 2(a) and with 2(b) applied voltage. At V = 0V the director is aligned along z because of anchoring. An applied voltage can induce reorientation. The resulting twist is larger in the regions where the inter-electrode separation is minimum (b) as compared to those where the separation is maximum (b + 2c). The low-frequency voltage applied between the electrodes has a double effect. Firstly, it creates an average increase of refractive index in a finite channel in y and parallel to z

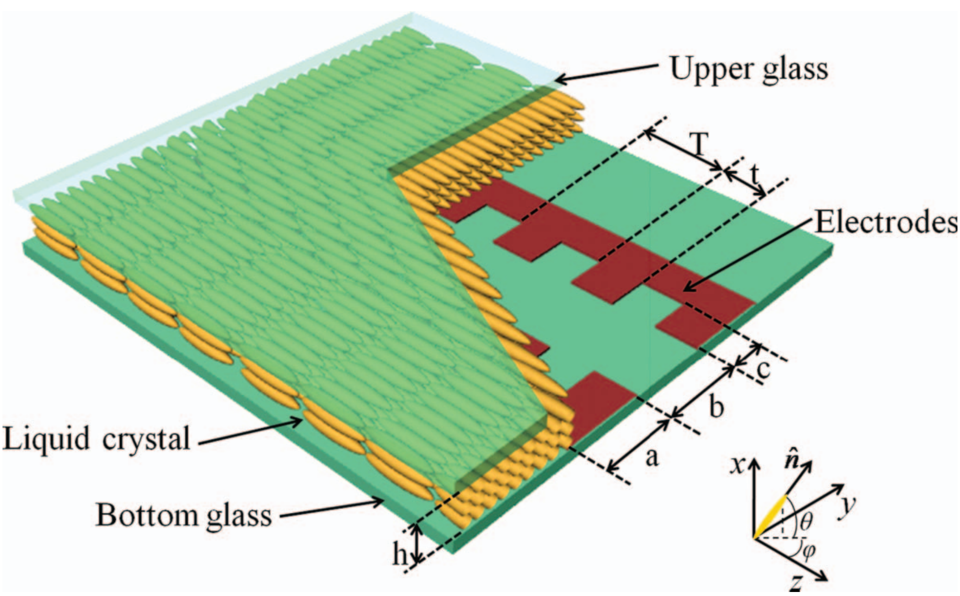

Figure 1. 3D view of the device.

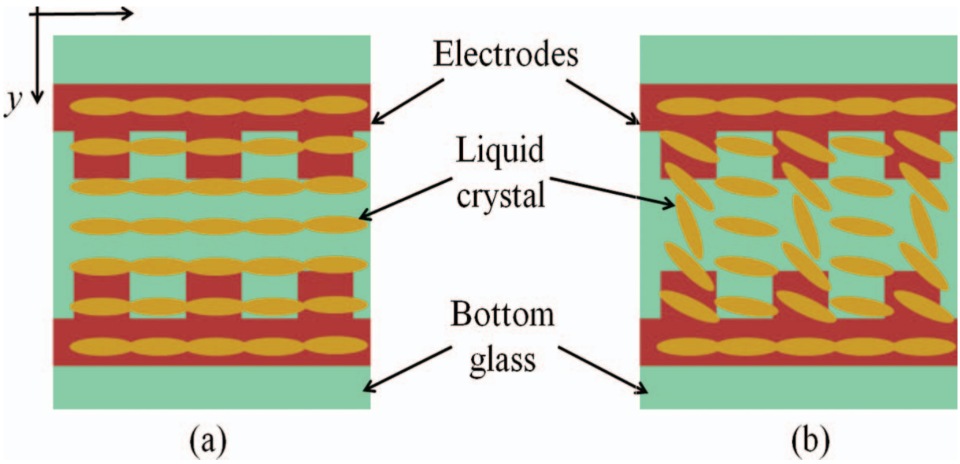

Figure 2. Liquid crystal reorientation above the electrode area for (a) V = 0 and (b) V > 0V.

with an additional periodic modulation and secondly it produces a 2D channel waveguide with a superimposed phase grating for TE propagation along *z*.

Device Analysis

We obtain the director distribution solving the voltage-dependent molecular reorientation, and finally we calculate the profile of the refractive index n_e for extraordinarily (e-) polarized light, i.e. for electric field vectors in the plane *xy*. Figures 3 shows the e-index profile for two values of the bias in two transverse sections along z, where the electrode separations are b + 2c ($z = 0$ μm) and b ($z = 0.25$ μm), respectively.

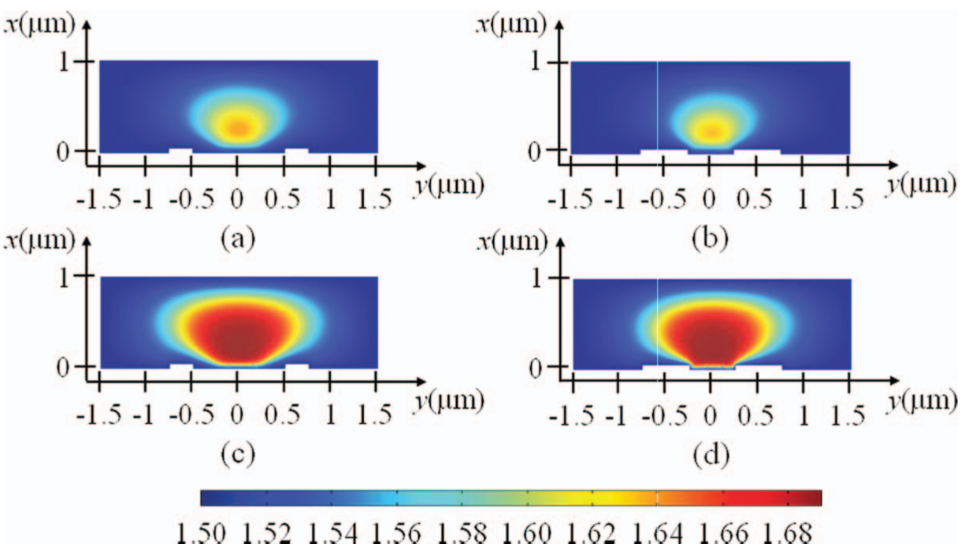

Figure 3. Refractive index profile for e-polarization in (a,c) $z = 0.25$ μm and (b,d,) $z = 0$ μm. The bias is 2.4 V in (a,b) and 5 V in (c,d).

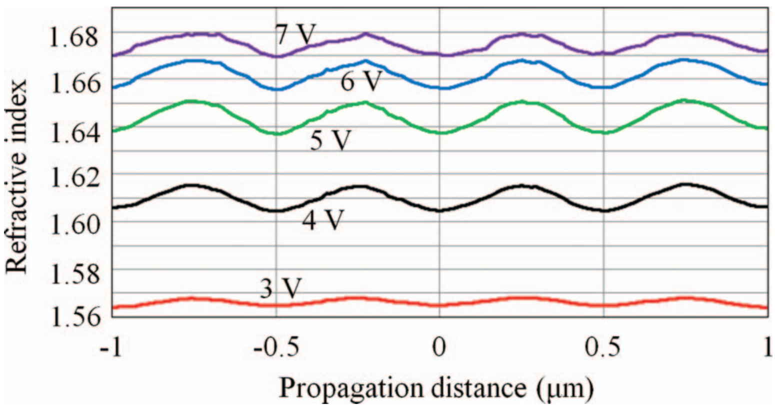

Figure 4. Refractive index modulation along z for applied voltages between 3 V (red bottom line) and 7 V (violet top line) in 1 V steps, evaluated 200 nm above the electrodes and in the symmetry axis between them ($y = 0$).

A beam propagator was used to calculate the transverse profile of the guided field distribution at a given wavelength and for each applied voltage. Due to the particular choice of parameters, only the fundamental order TE_{00} mode propagated in the structure. The periodic separation between the electrodes yields a modulated strength of E_y and, correspondingly, the index grating sought along z. Figure 4 displays the index modulation in a 6-period region along z, evaluated in $x = 0.2$ μm and $y = 0$ for various biases between 3 V and 7 V with a step of 1 V.

The modulation is sinusoidal with a 0.5 μm period, maximum when the electrode spacing is minimum (i.e. equals to b). Figure 5 graphs the resulting index contrast versus voltage between 0 and 13 V.

We can define four different zones for the voltage V: A) V < 2.4 V, the applied voltage is too low to create a grating; B) 2.4 V < V < 5 V the NLC, comprised in the region with minimum inter-electrodes distance, starts to reorient and for V = 5 V it reaches the saturation; C) 5 V < V < 12.3 V, only the un-saturated NLC region can still reorient,

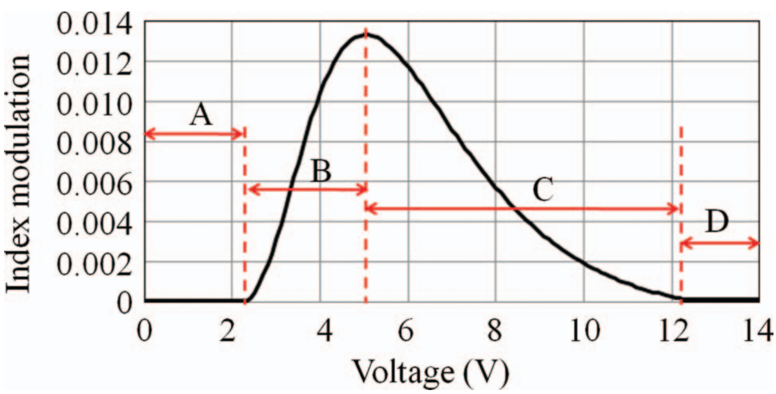

Figure 5. Longitudinal modulation versus applied voltage.

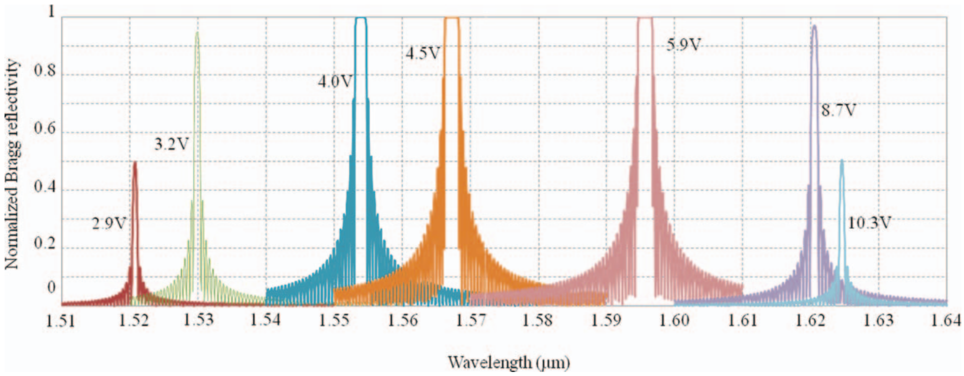

Figure 6. Normalized spectral reflectivity for various voltages and propagation over 1.5 mm (3000 periods), evaluated 200 nm above the electrodes and in the symmetry axis between them ($y = 0$).

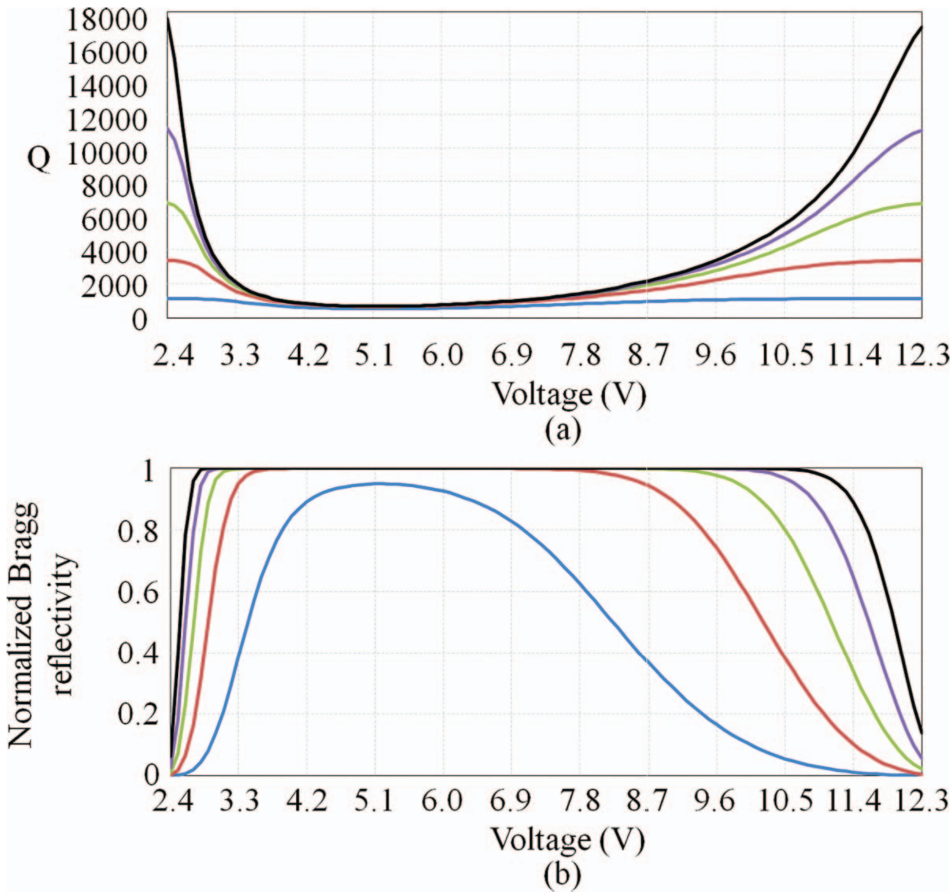

Figure 7. (a) Quality factor Q and (b) normalised Bragg reflectivity versus voltage for a few propagation lengths L in mm: 0.5 (blue), 1.5 (red), 3 (green), 5 (violet), 8 (black). All values are evaluated 200 nm above the electrodes and in the symmetry axis between them ($y = 0$).

resulting in a progressive reduction of the index modulation; D) V > 12.3 V the whole NLC is reoriented with director //*y* and a negligible index contrast.

Based on the e-index distribution and using coupled mode theory, we calculated the resonant Bragg wavelength for TE light propagating over 3000 periods, i.e. a grating length of 1.5 mm as shown in Figure 6.

The reflected wavelength at resonance red shifts with applied biases of a few volts, providing an extended tunability of ≈ 104 nm with a reflectivity R = 50% while maintaining a good spectral selectivity.

Figure 7(a) and 7(b) report the plots of the quality factor Q and the Bragg reflectivity versus bias respectively for various reflector lengths, from 0.5 to 8.0 mm. Q is defined as λ/FWHM, where FWHM stands for Full Width at Half Maximum representing the reflector optical bandwidth. Furthermore, it is worth to observe that modest change of the bias can significantly alter the reflectivity, for a given propagation length. For instance, R increases from 30 to 100% (70 to 100%) as the voltage changes slightly from 2.8 to 4.5 V, in the case of a length L = 1.0 mm (2.0 mm). The behaviour of Q is due to the FWHM, which increases when the index modulation increases.

Conclusions

We have proposed and numerically analyzed a tunable NLC waveguide Bragg reflector with a simple geometry and comb-shaped coplanar electrodes. The device provides transverse light confinement and periodic index modulation, yielding high reflectivity in a wide tuning range of 104 nm for voltages between 2.5 and 10.2 V. This novel geometry provides ease of fabrication and a simple electro-optic control. The tuning range of the proposed device is comparable or better than the largest values reported in literature and allows electro-optic operation throughout the whole C+L band of wavelength division multiplexing systems.

References

[1] T. E. Murphy, J. T. Hastings, and H. I. Smith, *J. Lightwave Technol.* **19**(12), 1938–1942 (2001).
[2] K. J. Kim, J. K. Seo, and M. C. Oh, *Opt. Express* **16**(3), 1423–1430 (2008).
[3] G. Jeong, J. H. Lee, M. Y. Park, C. Y. Kim, S. H. Cho, W. Lee, and B. W. Kim, *Photon. Technol. Lett.* **18**(20), 2102–2104 (2006).
[4] M. Kumar, T. Sakaguchi, and F. Koyama, *Appl. Phys. Lett.* **94**(6), 061112 (2009).
[5] J. Brouckaert, W. Bogaerts, S. Selvaraja, P. Dumon, R. Baets, and D. Van Thourhout, *Photon. Technol. Lett.* **20**(4), 309–311 (2008).
[6] R. G. DeCorby, N. Ponnampalam, E. Epp, T. Allen, and J. N. McMullin, *Opt. Express* **17**(19), 16632–16645 (2009).
[7] V. Maselli, J. R. Grenier, S. Ho, and P. R. Herman, *Opt. Express* **17**(14), 11719–11729 (2009).
[8] H. Zou, K. W. Beeson, and L. W. Shacklette, *J. Lightwave Technol.* **21**(4), 1083–1088 (2003).
[9] S. Honda, Z. Wu, J. Matsui, K. Utaka, T. Edura, M. Tokuda, K. Tsuitsui, and Y. Wada, *Electron. Lett.* **43**(11), 630–631 (2007).
[10] M. Kumar, T. Sakaguchi, and F. Koyama, *Opt. Lett.* **34**(8), 1252–1254 (2009).
[11] F. Heismann, L. L. Buhl, and R. Alferness, *Electron. Lett.* **23**(11), 572–574 (1987).
[12] A. Iocco, H. G. Limberger, R. Salathe, L. A. Everall, K. Chisholm, J. Williams, and I. Bennion, *J. Lightwave Technol.* **17**(7), 1217–1221 (1999).
[13] Y. Gong, L. Wang, X. Hu, X. Li, and X. Liu, *Opt. Express* **17**(16), 13727–13736 (2009).
[14] A. d'Alessandro, D. Donisi, L. De Sio, R. Beccherelli, R. Asquini, R. Caputo, and C. Umeton, *Opt. Express* **16**(13), 9254–9260 (2008).
[15] I. Fujieda, O. Mikami, and A. Ozawa, *Appl. Opt.* **42**, 1520–1525 (2005).

[16] L. Sirleto, G. Coppola, G. Breglio, G. Abbate, G. C. Righini, and M. J. Oton, *Opt. Eng.* **41**, 2890–2898 (2002).

[17] R. Asquini, A. d'Alessandro, C. Gizzi, P. Maltese, R. Caputo, C. Umeton, A. Veltri, and A. V. Sukhov, *Mol. Cryst. Liq. Cryst.* **398**, 223–233 (2003).

[18] A. d'Alessandro, D. Donisi, L. De Sio, R. Beccherelli, R. Asquini, R. Caputo, and C. Umeton, *Opt. Express* **16**, 9254–9260 (2008).

[19] C. S. Goh, M. R. Mokhtar, S. A. Butler, S. Y. Set, K. Kikuchi, and M. Ibsen, *Photon. Technol. Lett.* **15**(4), 557–559 (2003).

[20] F. Tian, C. Harizi, H. Herrmann, V. Reimann, R. Ricken, U. Rust, W. Sohler, F. Wehrmann, and S. Westenhofer, *J. Lightwave Technol.* **12**(7), 1192–1197 (1994).

[21] C. Conti, G. Assanto, and S. Trillo, *Opt. Lett.* **22**(17), 1350–1352 (1997).

[22] F. R. M. Adikan, J. C. Gates, A. Dyadyusha, H. E. Major, C. B. E. Gawith, I. J. G. Sparrow, G. D. Emmerson, M. Kaczmarek, and P. G. R. Smith, *Opt. Lett.* **32**(11), 1542–1544 (2007).

[23] I. C. Khoo, *Phys. Rep.* **471**(5–6), 221–267 (2009).